

A transformer-less DC-DC converter for grid-connected PV systems using TSTS-ZSI voltage boost-buck technique

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Abstract

This research introduces an innovative design for a grid-connected photovoltaic (PV) system utilizing a transformer-less DC-DC converter. The converter is based on the TSTS-ZSI (Three-Switch Transformer-less Z-Source Inverter) voltage boost-buck technique, which enhances voltage regulation and energy transfer, making it ideal for micro-inverter applications. The primary goal of the study is to improve energy efficiency while ensuring seamless integration with the grid. The proposed system not only boosts voltage but also ensures efficient buck operation, leading to enhanced power injection into the grid under fluctuating conditions. By utilizing advanced control techniques, the converter minimizes power losses, reduces stress on the components, and maintains stability in a wide range of grid scenarios. Simulations performed using MATLAB/Simulink demonstrate that the converter delivers stable and efficient power with minimal energy loss. The results validate its effectiveness in small-scale grid-connected systems, achieving enhanced power management under various operating conditions. The converter's ability to operate efficiently without a transformer reduces magnetic losses and electromagnetic interference, making it a cost-effective and compact solution. The research presents a valuable contribution to the field of renewable energy integration, with its applications extending to both residential and commercial grid-connected PV systems.

Keywords: Transformer-less; DC-DC Converter; Boost-Buck Technique; Voltage Regulation

1. Introduction

Today, DC-DC power converters are utilized in a wide range of applications, including fuel cell systems, hybrid car battery chargers, power factor correction (PFC), maximum power point tracking (MPPT) in photovoltaic (PV) systems, and maximizing energy harvesting from various renewable sources. With the growing demand for cleaner and sustainable energy, renewable technologies such as solar, wind, and fuel cells are becoming increasingly significant, and DC-DC converters are crucial for ensuring efficient energy conversion and system performance. In PV systems, DC-DC converters with MPPT algorithms are particularly essential, as they adjust the operating point of solar panels to maximize power output despite fluctuating sunlight conditions, improving the overall efficiency and reliability of solar energy generation [1-5]. Additionally, DC-DC converters are employed in wind energy and fuel cell systems, where they help stabilize and adjust voltage levels for grid connections or storage. Extensive research has been conducted to enhance the efficiency and reliability of DC-DC converters in renewable energy applications, with new topologies and control strategies continually emerging. Generally, these converters are categorized into Buck, Boost, and Buck-Boost types, with step-up (Boost) converters used to increase output voltage, when necessary, particularly in systems where low-voltage renewable sources, like solar panels or fuel cells, must meet higher voltage requirements. As renewable energy continues to expand, the role of efficient power converters becomes increasingly vital in ensuring higher energy efficiency and system viability [6-10].

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In 2011, a high-conversion-ratio DC-DC converter featuring switches, and a single-cell inductor was introduced. This development involved replacing inductors in traditional converters with a single inductor and adding a diode, leading to significant innovations in converters with a high conversion ratio. The addition of the diode results in a lower duty cycle and an increased conversion ratio. The diode helps with the transfer of inductive energy, which enables soft switching and facilitates the converter's shutdown when powered off. Using transistors or switches, the diode enables zero-voltage switching (ZVS), which reduces current and voltage stress, thereby improving efficiency. The increased magnetic coupling ratio between the inductor and its core plays a crucial role in enhancing efficiency and minimizing the overall size of the converter [11].

Also in 2024, a novel, significant uplift DC-DC converter based on a quasi Z-source that uses voltage multiplier cells and switching boost methods. In contrast to traditional Z-Source-based converters, this converter exhibits good efficiency in situations of high output voltage and greater output power, in addition to achieving high voltage gain. The majority of Z-source based converters have lower power operation and high current stress across the power MOSFETs. Other noteworthy benefits, however, include the removal of leakage current by offering the common grounded feature, extremely low input current ripple, low voltage and current stress across the power switches, and no duty ratio constraint [12].

An altered quasi-Z-source inverter with fewer switching elements. The output voltage of the suggested inverter has a reduced THD throughout a wide range of modulation index when compared to the Quasi-Z source cascade multilevel inverter (qZS-CMI). Both inverters are examined for the identical situation in order to highlight the better benefits of the suggested topology over the traditional qZS-CMI [13].

A novel quasi-resonant dc-dc boost converter architecture intended to raise the PV panels' output voltage in EV charging stations. In various operating modes, the correlations between voltage and current are examined. The suggested converter is noteworthy for its single power switch, which simplifies control. Additionally, it can minimize the size and cost of EV charging stations without requiring a transformer or connected inductor as compared to conventional DC-DC converters. The operation and performance of the proposed DC-DC converter is validated through the presentation of simulation and experimental data. [14].

A brand-new boost converter that uses only soft switching and has one auxiliary switch to provide Zero Voltage Transition (ZVT) for the primary switch while operating in Continuous Current Mode (CCM). To improve the efficiency and dependability of the converter, the auxiliary circuit offers gentle switching conditions for all switches and diodes in both turn-on and turn-off operations. Additionally, the EMI noise from switches and reverse recovery issues with diodes are reduced. To confirm theoretical studies and the viability of the suggested soft switching structure, simulation experiments are carried out in the PLECS program, and the results are given [15].

Additionally, a soft-switching isolated bidirectional DC-DC converter with an LCL resonant current-feed topology was introduced as an energy storage interface in DC grids. This converter used a half-bridge resonant converter and LCL circuit to achieve soft switching with semi-active devices. The selected dual-output topology used the resonant circuit to boost voltage and power efficiency, without the need for transformers or numerous switching circuits. High-frequency operation reduced the size of magnetic components and filters, improving efficiency. The converter's switches and diodes operated without significant magnetic interference during buck-boost operations [16-20].

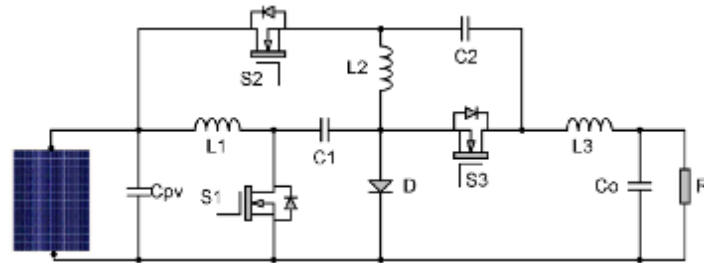
Finally, a high-efficiency DC-DC converter with a coupled inductor and high voltage gain was introduced to improve voltage levels while reducing losses [21]. This design used two coupled inductors to enhance performance compared to traditional multi-stage inductor-based DC-DC converters. The coupled inductors significantly increased the voltage conversion ratio, providing a higher voltage gain over a broad operating range [22-22].

This paper introduces a novel design for a transformer-less DC-DC converter specifically tailored for grid-connected PV systems. The proposed converter utilizes the TSTS-ZSI (Three Switches and a Transformer-less Z-Source Inverter) voltage boost-buck technique, making it highly suitable for micro-inverter systems. By efficiently increasing the voltage, this converter significantly enhances energy injection into the grid while maintaining system stability under varying conditions. This research demonstrates the converter's potential through MATLAB/Simulink simulations, showcasing its ability to achieve high power efficiency and effective voltage regulation for small-scale renewable energy systems.

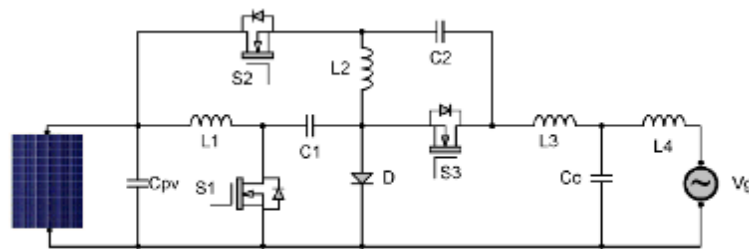
2. Material and methods

2.1. Analysis of Proposed converter

In this research, a single-phase converter without a transformer is presented, which provides a common ground between input and output and increases the voltage. The TSTS-ZSI voltage boost-buck technique in this converter increases the voltage higher than usual. The voltage increase in this single-phase converter makes it a good choice for use in micro single-phase converter systems.



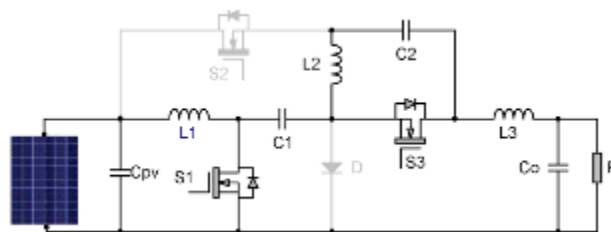
(a)



(b)

Figure 1 The used single-phase converter a: in the state separated from the grid and b: in the state connected to the grid

In Figure 1 (a), the converter used in an isolated state from the network is shown, which consists of three switches S_1, S_2, S_3 four capacitors C_{pv}, C_o, C_1, C_2 and three inductors L_1, L_2, L_3 . Additionally, in Figure 1 (b), the converter used in a state connected to the network is shown, where it is connected to an output filter of type LCL. In cases where the source is separated from the network and connected to the network, the converter acts as a voltage source. The converter operates sequentially as a current source. The semi-quasi-Z source is a common and well-known design that is formed in Figure 1 (a). For ease of analysis of the converter used, it is assumed that its combinations and components are ideal. In the presence of capacitors of sufficient size, therefore, their voltages remain constant during one cycle. In Figure 2, the operational states of the converter are depicted. The principles of operation are described as follows:



(a)

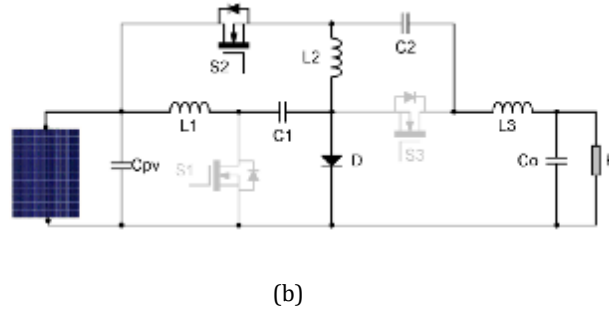


Figure 2 The working conditions of the used converter a: Mode 1 and b: Mode 2

2.1.1. State I:

In this state, the switches S_1, S_3 are turned on, while S_2 remains off, as illustrated in Figure 2 (a). In this case, the input voltage V_{in} is induced magnetically through the inductor L_1 . The energy flows into the circuit and capacitor C_1 is charged. Additionally, in this state, the equations are given by:

$$\begin{cases} V_{L1} = V_{in} \\ V_{L2} = -V_{C2} \\ V_{L3} = -(V_{C1} + V_o) \end{cases} \begin{cases} i_{C1} = i_{L3} \\ i_{C2} = i_{L2} \end{cases} \quad (1)$$

Where the volages of V_{L1}, V_{L2}, V_{L3} , and V_{C1}, V_{C2} are arranged to show the magnitude of the volages across L_1, L_2, L_3 , and capacitors C_1 and C_2 . The input voltage V_{in} and the output voltage V_o are arranged according to the current i_{L1}, i_{L2}, i_{L3} . In this state, the currents of capacitors i_{C1}, i_{C2} and inductors i_{L2}, i_{L3} are determined.

2.1.2. State II:

In this state, according to Figure 2 (b), the switch S_2 is turned on, while S_1 , and S_3 remain off. In this state, Inductor L_1 is charged capacitor C_1 . The input voltage is induced magnetically through the inductor L_2 , and the energy flows through the circuit. The capacitor C_2 discharges, and the equations for this state are as follows:

$$\begin{cases} V_{L1} = V_{in} - V_{C1} \\ V_{L2} = V_{in} \\ V_{L3} = V_{in} + V_{C2} - V_o \end{cases} \begin{cases} i_{C1} = i_{L1} \\ i_{C2} = -i_{L3} \end{cases} \quad (2)$$

By applying the principles of volt-second balance to inductors L_1 and L_2 , the capacitor volages C_1 and C_2 can be derived as follows:

$$V_{C1} = \frac{1}{1-D} V_{in} \quad (3)$$

$$V_{C2} = \frac{1}{1-D} V_{in} \quad (4)$$

Where D represents the duty cycle of switches S_1 and S_3 . By using equations (3) and (4) alongside the volt-second balance principle in inductor L_3 , the voltage boost in the applied converter can be determined according to equation (5).

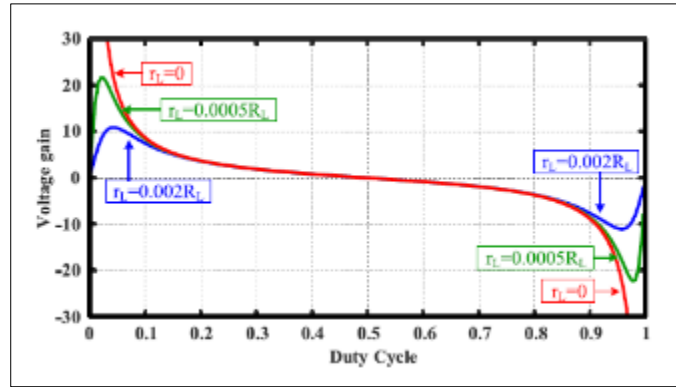


Figure 3 Voltage increase against the duty cycle of the used converter, considering the parasitic components

Considering the output voltage V_o as constant, the minimum input voltage V_{inmin} of converter can be calculated by increasing its maximum voltage.

$$\frac{V_o}{V_{in}} = \frac{1-2D}{D(1-D)} \tag{5}$$

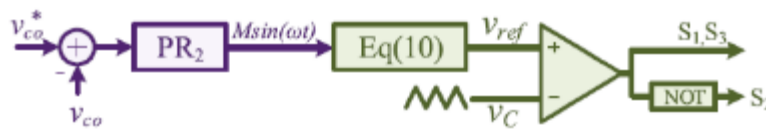
2.2. Control of the proposed converter

The control diagram of the converter used in both grid-connected and off-grid modes is depicted in Figure 4 (a) and (b). In the off-grid mode, the output VCO is controlled until an AC sinusoidal output is provided. A proportional-resonant (PR) controller in a loop produces a sinusoidal signal (ωt), like a phase-locked loop (PLL), followed by a filter to convert the resulting signal to pulses for different switching activities [27-28]. In Figure 4 (b), the maximum power point tracking (MPPT) unit first generates the power from the PV panel. Then, this reference voltage error is fed into a combined proportional-integral (PI) controller [29]. The resulting output is compared with the reference signal to control the output current of the converter. The output current of the converter is created in the output phase. The resulting reference signal is closed-loop, and the signal is used to control the output current of the converter via the PR and PI controllers, as illustrated in Figure 4 (a). The equations of the PI and PR controllers [30] are given as follows:

$$PI(S) = K_p + \frac{K_i}{S} \tag{6}$$

$$PI(S) = K_p + \frac{K_R \times s}{S^2 + K_C \times s + \omega^2} \tag{7}$$

K_p, K_i, K_R, K_C are the control parameters.



(a)



(b)

Figure 4 The block diagram of controller; (a) islanded mode, (b) grid-connected mode

3. Results and discussion

In this section, simulation results for the structure of a grid-connected solar system with high efficiency and performance are presented. The simulation results are done using MATLAB/Simulink software. In this paper, a three-switch converter without common ground is used. The total simulation time is 0.12 seconds. The system is connected to a 220-volt, 50-hertz single-phase grid. In this simulation, instead of a panel, a DC source is used, which applies 350 volts to the converter. The implementation of the three-switch converter without a common ground in the MATLAB/Simulink environment is shown in Figures 5 and 6.

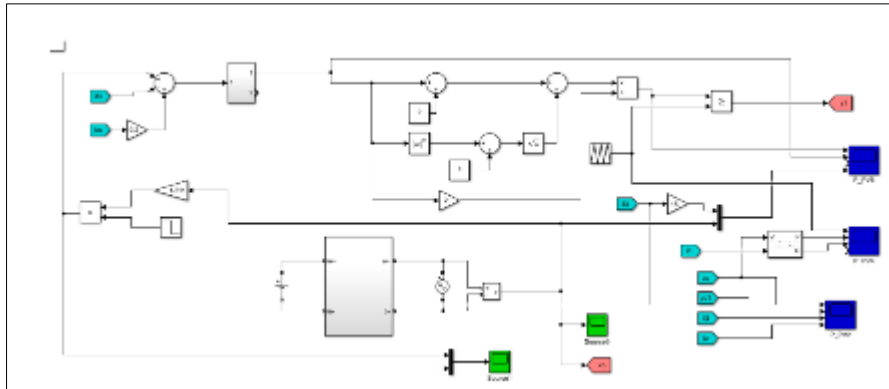


Figure 5 The whole schematic of system.

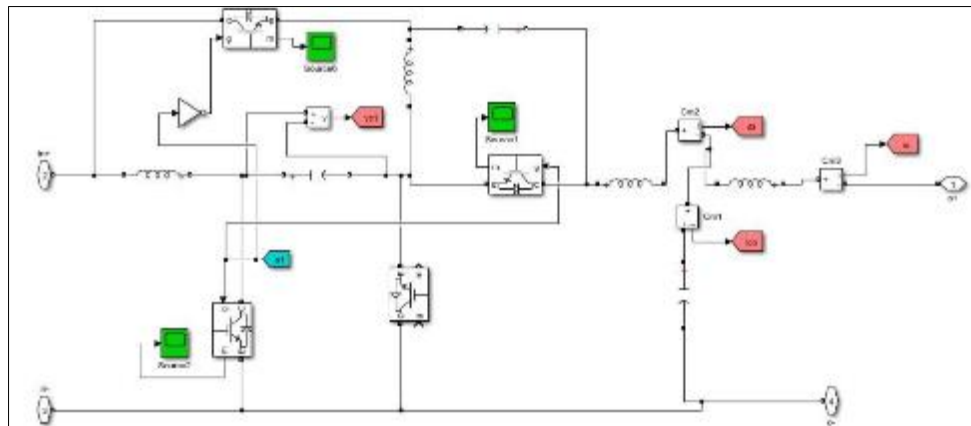


Figure 6 The structural form of the three-switch converter without a common grounded transformer in MATLAB/Simulink.

The electrical parameters of the proposed converter are shown in Table 1. Also, in grid-connected mode, the values of the control system are set in such a way that the proposed inverter has the best performance.

Table 1 Parameters of the proposed converter

Parameters	Value
Capacitor C_1	20 μ F
Capacitor C_2	10 μ F
Inductor L_1 and L_2	220 μ H
Inductor L_3 and L_4	4 mH
Switching Frequency	40KHz

Input Voltage	350V
Grid Voltage	310V

The applied voltage to the inverter is suggested to be equal to 350 V DC. As shown in Figure 7, the grid voltage is the same as the output voltage, which equals 311 V peak-to-peak and 220 V effective voltage.

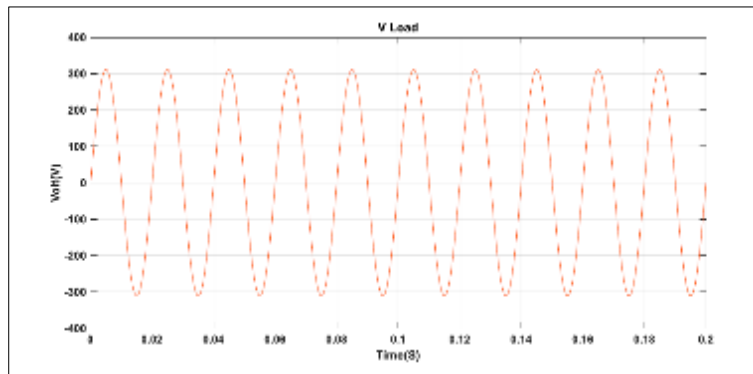


Figure 7 Applied voltage to the proposed converter.

According to the circuit structure, the current i_{L4} that passes through is equal to the current from the inverter suggested to be injected into the network. This is shown in Figure 8.

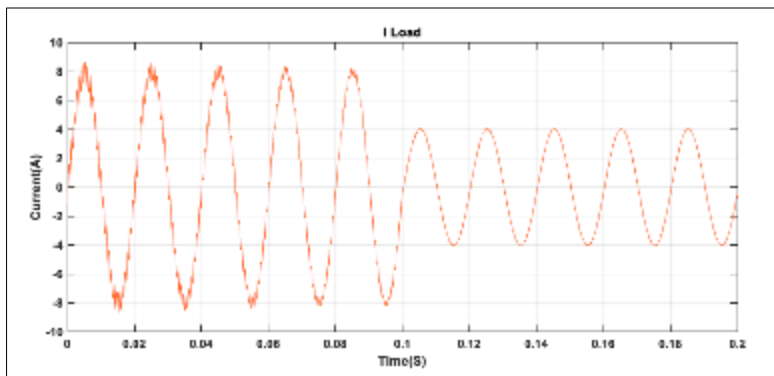


Figure 8 The injected current to the grid.

As seen in Figure 8, the amount of the delivered current to the network increases up to $t=0.1t = 0.1t=0.1$ and reaches 8 Amps, and after this point, a control system with a value of 4 Amps is applied to the current, which shows the correctness of the control system's function. In Figure 9 (a), the delivered active power to the network is equal to the multiplication of voltage and current:

$$P_{out1}=220 \times 8 / \sqrt{2} = 1244.6 \text{ W}$$

$$P_{out2}=220 \times 4 / \sqrt{2} = 622.2 \text{ W}$$

In Figure 4-5, it is observed that the power increases up to $t=0.1t = 0.1t=0.1$ to 1244 W and then stabilizes at around 622 W Losses cause a slight discrepancy. In Figure 9 (b), the reactive power of the inverter is observed.

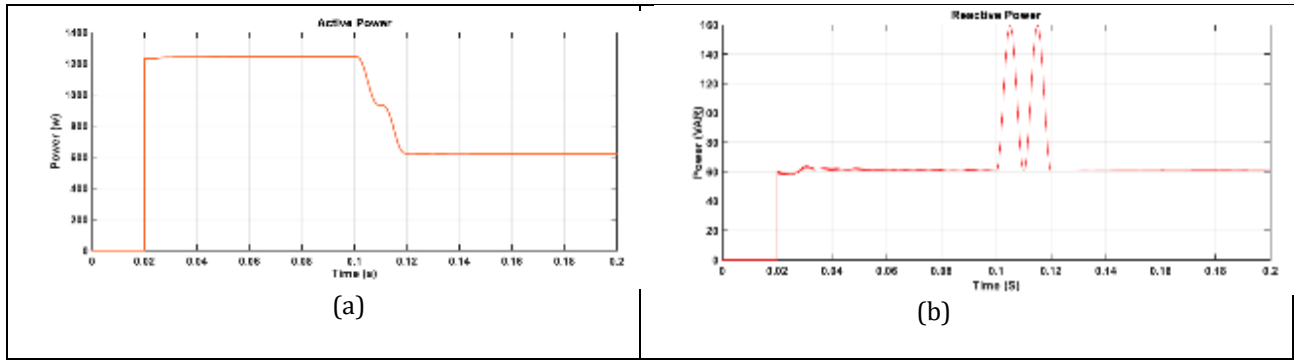


Figure 9 (a) Active power and (b) reactive power of proposed converter.

As shown in the circuit diagram, when switch S_2 is on and switches S_1 and S_3 are off, the inductor L_1 charges capacitor C_1 . The voltage of capacitor C_1 is observed in Figure 10. The voltage of output capacitor of converter in grid connected mode is shown in the figure below.

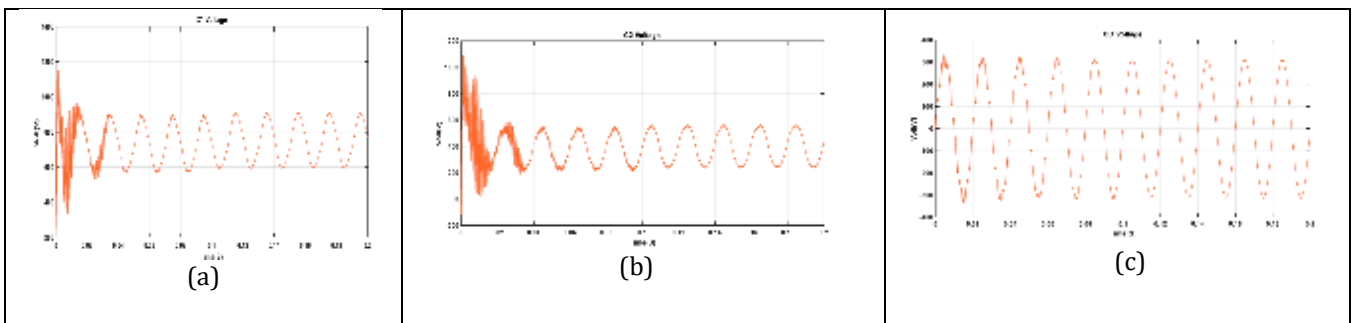


Figure 10 The voltage of capacitors; (a): C_1 , (b): C_2 , (c): C_o

The switching voltage of switches S_1 , S_2 , and S_3 is represented in Figure 11 :

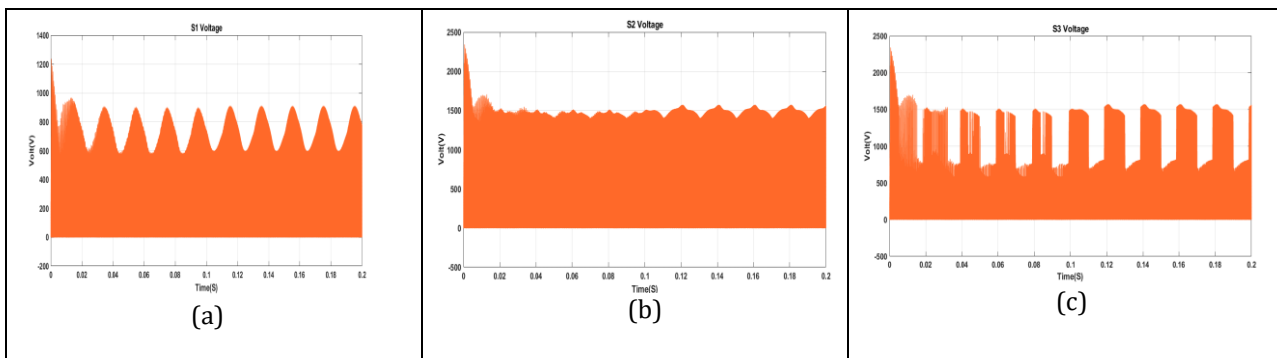


Figure 11 The voltage of switches; (a) S_1 , (b) S_2 , (c) S_3

4. Conclusion

The proposed three-switch transformer-less DC-DC converter, utilizing the TSTS-ZSI voltage boost-buck technique, presents a substantial advancement in energy management for grid-connected photovoltaic (PV) systems. Its transformer-less design simplifies the system architecture while enhancing efficiency by reducing magnetic losses and electromagnetic interference. The converter delivers stable power under varying grid conditions, validated through detailed MATLAB/Simulink simulations, making it suitable for micro-inverter applications in residential and commercial PV installations. A key advantage is the high conversion ratio with reduced voltage stress on components, extending their lifespan and improving system reliability. The converter's operation in both grid-connected and off-grid modes, controlled by proportional-resonant (PR) and proportional-integral (PI) controllers, ensures optimal performance across different operating scenarios, enhancing its flexibility and efficiency in diverse applications. In addition, the control mechanisms allow for precise voltage regulation and efficient power injection into the grid,

maintaining stability under fluctuating load and grid conditions. The PR and PI controllers ensure smooth operation with minimal harmonic distortion, ensuring compliance with grid standards. This adaptability makes the converter a practical solution for integrating renewable energy sources into the grid. In conclusion, the three-switch transformerless DC-DC converter offers an efficient and reliable approach to enhancing the performance of small-scale renewable energy systems, particularly in grid-connected PV setups. Its innovative design and control methods contribute to improved efficiency, making it an asset for future renewable energy applications. Further research could explore optimizing its performance for larger grid-connected systems.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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